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ON OBTAINING METEOROLOGICAL RECORDS IN THE UPPER AIR BY MEANS OF KITES AND BALLOONS.

By A. Lawrence Rotch.

Presented January 13, 1897.

A knowledge of the physical conditions which prevail up to the highest cloud levels, five to nine miles above the earth, is of great importance to meteorologists, who until recently have been studying principally the conditions existing near the floor of the aerial ocean, and from that standpoint have endeavored to formulate the laws which control the pressure, temperature, humidity, and currents in the great volume of air above them. Continued and systematic observations on mountains in different parts of the world latterly have contributed much to our knowledge of the approximate conditions of the atmosphere, under various circumstances, up to a height of more than three miles above sea level, but the mass and surface of the mountain, even when this is an isolated peak, influence very considerably the surrounding air. Recognizing, then, the value of the determination of the true conditions of the free air, let us consider what methods are available for this investigation, which must necessarily be sporadic and of shorter duration than if conducted on mountains. In the writer's opinion, free balloons with aeronauts cannot be recommended on account of the large cost in money, and sometimes the loss of life, which attend their frequent use, while without artificial aids to respiration the aeronaut cannot rise much above five miles. Captive balloons, with observers, have been used in England, and more recently, with self-recording instruments, in Germany, but their height is limited to about two thousand feet by the weight of the lifted cable, and a wind which is sufficient to overcome their buoyancy drives them down and occasions violent shocks to the suspended instruments. A kite-balloon on trial in the German army is intended to combine the advantages of a kite and a balloon, but the cost and the moderate height attainable render it inferior to the simple kite

for meteorological researches, except during calms which sometimes occur at the earth's surface, but rarely extend aloft.

There remain kites and unmanned balloons, both recording graphically and continuously the chief meteorological conditions, and these it is my intention to describe in this paper. The recent development of the kite for meteorological purposes has taken place in the United States, while the use of the automatic balloon for obtaining data at very great altitudes has hitherto been confined to Europe.

Kites appear to have been first applied in meteorology by Alexander Wilson, of Glasgow, who in 1749 raised thermometers attached to the kites into the clouds.* Three years later, Franklin performed in Philadelphia his celebrated experiment of collecting the electricity of the thunder-cloud by means of a kite.† Although kites have served a variety of purposes, their first systematic use in meteorology was probably in England, between 1883 and 1885, when E. D. Archibald made differential measurements of wind velocity by anemometers raised by kites fifteen hundred feet.‡ In 1885, A. McAdie repeated Franklin's kite experiment on Blue Hill, using an electrometer,§ and in 1891 and 1892 made simultaneous measurements of electrical potential at the base of Blue Hill, on the hill, and several hundred feet above it with kites as collectors.‖ The invention of light-weight self-recording instruments made it possible to obtain graphic records in the air by means of kites, and after W. A. Eddy had introduced tailless kites into this country, and had attached a minimum thermometer in 1891,¶ a thermograph reconstructed of lighter materials by S. P. Fergusson, of the Blue Hill Observatory, was raised on August 4, 1894, 1430 feet above the hill.** It was no doubt the first instrument, recording continuously and graphically, to be lifted by kites, and it permitted simultaneous observations to be obtained in the free air and near the ground. This method of studying the meteorological conditions of the free air has ever since been in regular use at the Blue Hill Observatory; but notwithstanding the general interest which has recently been aroused in kites, it is not known by the writer that meteorographs have elsewhere been raised by them.

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* Trans. Roy. Soc. of Edinburgh, Vol. X. Part II., pp. 284–286.

† Sparks's Works of Benjamin Franklin, Vol. V. p. 295.

‡ Nature, Vol. XXXI.

§ These Proceedings, Vol. XXI. pp. 129–134.

‖ Annals Astr. Obs. Harv. Col., Vol. XL. Parts I. and II., Appendices A and C.

¶ Am. Met. Journal, Vol. VIII. pp. 122–125.

** Ibid., Vol. XI. pp. 297–303.

The details of the work, as now carried on at Blue Hill, are as follows. The kites, which have no tails, are of Eddy's Malay, or of Hargrave's cellular types, the former presenting a convex surface to the wind, and the latter two pair of superposed planes, each pair being connected by side planes. In addition to the two leading kites, others are attached by independent cords to various points of the line, which is a steel music wire, 0.033 inch in diameter, having a tensile strength of three hundred pounds, and weighing fifteen pounds per mile. The meteorographs are composed mostly of aluminium and weigh less than three pounds each, the one constructed by J. Richard, of Paris, recording on a single clock cylinder atmospheric pressure, air temperature, and relative humidity, while that made by Mr. Fergusson similarly records wind velocity and air temperature. One of these instruments is hung to the wire between two kites, in order to insure its safety in case of breakage of the wire or of one kite, or the failure of the wind to support the latter. The wire is coiled upon the drum of a windlass, which may be turned by two men, and a measuring device registers the amount of wire uncoiled, while the angular elevation of the meteorograph, when not hidden by clouds, is observed from time to time with a surveyor's transit at the windlass or at the ends of a base line. From these data, or from the barometric record, the altitude of the meteorograph is calculated. Kites may be flown in all kinds of weather, whenever the wind's velocity is between fourteen and thirty-five miles an hour; and since on Blue Hill the average velocity is more than eighteen miles an hour, days are frequent when flights are possible.

Probably the greatest elevation yet attained by kites, and certainly the highest level to which kites have lifted a meteorograph, is 8,740 feet above Blue Hill. This was accomplished, October 8, 1896, by the aid of nine kites, having a total area of 170 square feet, which gave a maximum pull at the ground of about 100 pounds.* The meteorograph remained during several hours higher than a mile, and good records of the indications of the barometer, thermometer, and hygrometer were brought down. More than one hundred records of atmospheric pressure, temperature, and relative humidity of the air, or wind velocity, at intermediate heights up to the extreme altitude just stated, have been obtained, and they are being discussed for publication with the Blue Hill observations for 1896, in the "Annals of the Astronomical Observatory of Harvard College." A few general conclusions may be mentioned. At the height of about a mile the diurnal changes of temperature in the free air nearly disappear, although

* Science, Nov. 13, 1896, p. 718.

in fair weather the days are damper than the nights. "Cold and warm waves" commence in the upper air, as is proved by the temperature decreasing faster than normal, or even increasing abruptly, with altitude before the fall or rise of temperature commences at the earth's surface. Several ascents through clouds have shown the air above them to be usually warmer and drier than the air below. Kites furnish a ready and accurate method of measuring the heights of certain low and uniform clouds, which could not easily be measured otherwise in the daytime. It is interesting to note that this method was used by Espy, about 1840, to verify his calculations of the height at which condensation begins.* Changes of wind direction in the different air strata are determined from the azimuths of the kites, and this change sometimes amounts to 180°. The wind velocity usually increases with altitude, and vertical currents commonly prevail near cumulus clouds. During high flights the wire is strongly charged with electricity, but no measurements of its kind or potential have lately been attempted.

The writer is glad to acknowledge his indebtedness to his assistants, Messrs. Clayton and Fergusson, who have devised and constructed improved kites and apparatus, and during his absence have taken entire charge of the work. To them and to another assistant, Mr. Sweetland, is largely due the success which has been attained in this novel branch of research. For still higher ascents there will be required a steam engine to operate the windlass, and a meteorograph with a lower pressure scale. With these appliances, for whose purchase a grant has been asked from the Hodgkins Fund of the Smithsonian Institution, it is probable that records can be obtained three miles above Blue Hill, and possibly higher.

To reach much higher altitudes, unmanned free balloons, or "ballons sondes" as they are called, have been considerably used both in France and Germany. These balloons, which carry self-recording apparatus, rise until equilibrium is attained in the rarefied air. When they lose their buoyancy and fall to the earth, most of them have been recovered, with the instruments and records uninjured, by the senders, who have been notified by the finder of the place of descent, which is often at a great distance from the starting point. The altitudes are calculated from the barometric pressure, according to Laplace's formula, but the impossibility of knowing the mean temperature of the whole mass of air makes the determination inexact. Theoretically, in order to ascend ten miles

* Philosophy of Storms, 1841, p. 75.

above the earth, where the pressure is about one ninth that at the earth, the balloon must lift itself from the ground when one ninth filled with gas. Therefore a relatively large balloon is required, and its initial velocity of ascent is great, because it is found advantageous to fill the gas-bag completely. The greatest difficulty has been to protect the thermometers from insolation, and to insure records being made, notwithstanding the great cold to which the instruments are exposed.

The first systematic experiments of the kind were made in Paris, in 1893, by G. Hermite, who was later associated with G. Besançon. There have been six high ascents from Paris of the three balloons called *L'Aérophile*. The second one of the name had an envelope of gold-beaters' skin, with a capacity of 6,360 cubic feet, which when nearly filled with coal-gas gave an initial lifting power of 235 pounds, in excess of its own weight of 49 pounds, and the instruments and screens, which weighed 12 pounds. With this balloon, in October, 1895, at an approximate height of 46,000 feet, a temperature of —94° Fahrenheit was recorded, which is the lowest noted in a balloon, and probably the lowest natural temperature observed on the earth. The average decrease of temperature was 1° Fahrenheit for 320 feet of height. The instruments used are of the well known Richard type, and have been tested in a chamber whose pressure and temperature are lowered to the limits which it is expected may be reached by the balloon. They are placed below the balloon in a wicker tube six feet high, lined with silvered paper to ward off the sun's rays. It is believed by Hermite, that during the rapid ascent of the balloon the draught of air through the tube is sufficient to neutralize the heating of the enclosed air by the sun. It is admitted that when equilibrium is nearly reached this may not be true, and that the temperature recorded near the highest point may be too high. To avoid freezing of the ink the registration is now made on smoked paper, and to protect the instrument from shocks it is hung by springs in a closed basket, which is itself suspended in the tube already mentioned. An apparatus for obtaining samples of air at high altitudes has been carried by the balloon, but as yet without success, owing to difficulties in hermetically closing the receiver after the air has entered, since mechanically closing the inlet tube and sealing it by heat generated chemically have each proved ineffectual at great heights.

By means of a grant from the German Emperor to the Deutsche Verein zur Förderung der Luftschiffahrt, R. Assmann, A. Berson, and others in Berlin, have been able to carry on an extensive series of meteorological investigations with manned balloons, and also with a captive

and a free balloon, both equipped with self-recording instruments. The latter, called the *Cirrus*, of 8,830 cubic feet capacity, when inflated with coal-gas had a lifting force of about 290 pounds, besides its envelope weighing 93 pounds, and the meteorological apparatus weighing nearly 6 pounds. This is more complicated than the French instruments, since the registration is photographic, and a continuous ventilation of the alcohol thermometer in Assmann's aspiration apparatus is effected by allowing a weight to drive the aspirator. Even with these precautions, the temperatures are probably too high, and the registration is often defective. There have been seven flights of the *Cirrus*, one of the highest occurring in September, 1894, when the unprecedentedly low barometric pressure of about two inches of mercury was recorded, giving a computed height of 60,500 feet. The lowest temperature, which was registered at a somewhat less altitude, was not below —88° Fahrenheit, giving rise to the supposition that the thermometer was heated by insolation. Hence the average decrease of temperature appears to have been but 1° in 409 feet. This balloon rose from Berlin with the great velocity of about 30 feet per second, and travelled 560 miles in an east-northeast direction at a velocity of 83 miles per hour.

For some time past negotiations have been in progress between the French and the Germans for simultaneous ascents of unmanned balloons at night, using identical instruments, whereby the errors due to insolation, and the discrepancies which might be attributed to different instruments, would be avoided. By this co-operation the simultaneous conditions of the upper air over a wide extent of country can be ascertained, just as these conditions near the earth's surface are daily obtained at the meteorological stations in the different countries. The desired result was brought about by the International Meteorological Conference which met last September in Paris. Resolutions were adopted favoring scientific ascents with manned balloons, as well as simultaneous flights of unmanned registration balloons in the different countries. The successful use of kites at Blue Hill to lift self-recording instruments over a mile into the air, led to expressed desire that similar experiments should be tried elsewhere. An international committee was appointed to carry out these resolutions, consisting of Messrs. de Fonvielle and Hermite for France; Assmann, Erk, and Hergesell for Germany; Pomortzeff for Russia; and the writer for the United States. In accordance with the first named resolutions, a flight of four manned and four registration balloons occurred in France, Germany, and Russia on the night of November 13–14 last. Owing to hurried preparations, only the registration balloon liberated from Paris

reached a great height; but in presenting a summary of the results to the French Academy,* E. Mascart, the director of the French Meteorological Office, remarks that there is reason to hope that this international co-operation will contribute valuable data to our knowledge of the variations of temperature and wind in the upper atmosphere.

As the American representative of the International Aeronautical Committee, the writer hopes that in this country a similar exploration of the high atmosphere with registration balloons will be attempted, and he is now preparing an estimate of the cost to submit to the trustee of the Hodgkins Fund. Since it should supplement his own researches with kites which are described first in this paper, he has taken the occasion to bring the subject of free registration balloons to the attention of the Academy.

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* Comptes Rendus, Vol. CXXIII. No. 22, pp. 918, 961.